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SUMMARY

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The initial rate of increase of the luminosity produced by 1/8-inch-diameter aluminum spheres impacting aluminum targets at a nominal velocity of 2.5 km/sec in air at pressures from 4×10^{-4} to 2×10^{-1} torr (mm of Hg) was found to vary approximately as the 1/3 power of ambient pressure. Radiation produced solely by the cratering mechanism did not contribute significantly to the observed variation of impact flash. Luminosity produced by the interaction with the atmosphere of ejecta of particle radii greater than 10^{-5} cm and at velocities from 8 to 16 km/sec is consistent with the observed flash. The impact flash of the present tests is thus primarily if not completely an atmospheric phenomenon.

At the low ambient pressures of the present tests, spectral lines and bands characteristic of the target and projectile material have been identified in impacts of aluminum projectiles into the following targets: (a) aluminum, (b) aluminum coated with sodium silicate, and (c) solid basalt rock. At a higher atmospheric pressure of 400 torr, spectra of impact flash produced in air differed significantly from that produced in nitrogen. Author

INTRODUCTION

In the laboratory, a flash of light is generally seen to accompany hypervelocity impact. The principal features of this flash are the elements of light emanating from the point of impact. The flash may be studied to determine characteristics of the impact phenomenon.

Early work in this field has been conducted at the University of Utah by Clark, Kadisch, and Grow (ref. 1). They found that atomic copper spectral lines are the predominant feature of the flash obtained from impacting copper spheres into copper targets at a velocity of 2.2 km/sec in an atmosphere of argon at a pressure of 60 torr. In an atmosphere of hydrogen at a pressure of 635 torr, however, the line structure is not detectable, and the flash is dimmer by at least two orders of magnitude. Clark concluded that impact flash results primarily from the collisions between spray particles ejected from the crater and the surrounding atmosphere, and thus presented a qualitative theoretical explanation for the above observations (see Theoretical Considerations). On the other hand, Gehring and Sieck (ref. 2) studied the flash from the impact of nylon spheres with sand targets at velocities of 2.1, 2.6, and 3.1 km/sec, and found, in tests with air at pressures from 4×10^{-2} to 80 torr and with helium at pressures of 4 to 76 torr, no apparent significant effect of the composition or the pressure of the gas surrounding the area of impact on the magnitude of the impact flash.

The present investigation received its initial impetus from a proposal, by Dr. John O'Keefe of Goddard Space Flight Center, to drop a mass on the dark side of the moon, observe the spectrum of the flash produced on impact and so determine the chemical constitution of the lunar surface. Clearly, if an impact takes place at the surface of the moon, which is thought to have an atmospheric pressure of less than 10^{-9} torr (ref. 3), or in the near vacuum environment of space, the atmospheric dependency of flash may be the critical factor in determining whether sufficient radiation for detection is produced. Therefore, the present investigation of the mechanism of flash resulting from hypervelocity impact was undertaken.

Presented are experimental data on the initial rate of increase of luminosity and spectrum of radiation due to the impact of aluminum projectiles into aluminum and basalt rock targets in air, nitrogen, and a mixture of the two, at low ambient pressures and at a nominal impact velocity of 2.5 km/sec. This velocity is approximately the lunar escape speed and the proposed impact velocity of the Ranger rocket on the moon. Also discussed in this report are two proposed mechanisms for impact flash: first, the radiation produced by ejecta interacting with the atmosphere at low ambient pressures in the same manner as meteors in the free molecule regime (for which the ejecta particle size is much less than the mean free path of the atmospheric particles), and second, the radiation resulting from the mechanism of cratering (which is independent of the atmosphere).

THEORETICAL CONSIDERATIONS

Description of Possible Flash-Producing Mechanisms

The spectrum of a self-luminous event will, in general, consist of line spectra emitted by atoms, band spectra emitted by molecules, and a continuum emitted either from the hot surfaces of liquids and solids or from the acceleration or capture of charged particles. In an impact event, all of these kinds of spectra may be expected to be present.

For the emission of line and band spectra, the atoms and molecules from which the radiation emanates must be free; that is, they must be in the vapor state. In impact, atoms and molecules from the target and projectile material may be vaporized by the cratering process alone or by the aerodynamic heating of material ejected from the crater. The vaporized atoms and molecules can be excited by absorbing radiation or by collision with other atoms or molecules, either in the ambient atmosphere or in the shock heated impact region itself. Energy leading to excited vibrational and electronic states can be accepted by the atom or molecule only in discrete quantities or quanta. The excited atom or molecule will then naturally decay in about 10^{-8} second to a lower state by the emission of a photon unless it collides in the meantime with another particle which may stimulate emission or take away energy.

Continuum radiation will result from the shock heated projectile and target material and from the aerodynamic heating of ejecta. Another source of radiation is chemical combination. This is particularly true if the materials which undergo heating are capable of burning in the atmosphere in which the impact takes place.

Threshold Velocity for Excitation of Atoms by Collisions

The primary process of excitation of atoms and molecules is by collision with other particles. Let us consider a collision between two particles of mass m_1 and m_2, from which a photon of energy $h\nu$ may be emitted. Let particle 2 be initially at rest and particle 1 have the velocity V. The equations for the conservation of energy and momentum are

$$(1/2)m_1V^2 = (1/2)m_1v_1^2 + (1/2)m_2v_2^2 + h\nu$$

$$m_1\overline{V} = m_1\overline{v}_1 + m_2\overline{v}_2 + (h\nu/c)\overline{k}$$

where v_1 and v_2 are the respective particle velocities after scattering and emission, h is Planck's constant, ν the frequency of the emitted radiation, and c the velocity of light. The bars in the momentum equation indicate vectors and $\overline{k}$ is a unit vector in the direction of propagation of the photon. Solving these for a minimum V, for a photon of frequency ν_o (in relation to the rest frame of the emitting atom) to be emitted, we arrive at a threshold equation for the relative velocity between the two particles.

$$V_{min} = \sqrt{\frac{2(m_1 + m_2)h\nu_o + (h\nu_o/c)^2}{m_1m_2}}$$

The following table contains values of V_{min} computed from this equation. For each value, particle 1 is an aluminum atom and ν_o, the frequency of radiation emitted by an aluminum atom when an electron jumps from its first excited state to the ground state, is 7.57×10^{14} sec^{-1} (3962 Å).

Particle 2	V_{min}, km/sec
Lead atom	5.0
Aluminum atom	6.7
Nitrogen molecule	6.6
Argon atom	6.1
Helium atom	13.2
Hydrogen molecule	17.9

In an impact event, atomic and molecular collisions of the type just considered may take place in two regions: (1) in the shocked impact region of the target and projectile and (2) in the ambient atmosphere.

The first region is formed on impact as shock waves are sent into both the target and projectile from their impact interface, leaving the material behind the advancing shock waves in a state of high pressure and temperature. To give meaning to the table consider an aluminum atom originally in the projectile and now engulfed in this shocked region. This atom will collide with like aluminum atoms of the projectile and also, if originally situated near the impacting surface, may collide with atoms or molecules of the target. For the former case the table shows that the V_{min} required for excitation of the aluminum atom is 6.7 km/sec and for the latter, if the target is for example, lead, V_{min} is 5.0 km/sec. The impact process is not well understood, and the thermodynamic properties of materials under high pressures are not fully known, so atomic and molecular collisions producing excited electron states may occur within this region even though the impacting velocity is less than the V_{min} required for the materials involved.

In the second region, the ambient atmosphere, collisions will take place between the atmospheric particles and atoms and molecules ejected from the crater, or vaporized from ejected material. If part of the ejecta have velocities equal to or greater than the V_{min} for the particles involved, radiation should result. The table shows that this radiation should depend upon atmospheric composition (Clark's result). An effect of atmospheric pressure can also be anticipated. If all variables except atmospheric pressure are held constant, higher ambient pressure and therefore density should result in more frequent atomic collisions and, hence, in a compressed time scale for the impact flash and a correspondingly higher rate of increase of luminosity. Information is available on the velocities of discrete-sized particles in the ejecta as contrasted to atomic particles. This information may, however, indicate the magnitude of the atomic and molecular velocities as well.

Velocities of Ejecta

A small percentage of the total ejecta from a crater has been observed to have velocities greater than the impact speed (ref. 4). This high-speed matter is associated with the jetting observed during the explosive collapse of a conical liner of a shaped charge, the collision of two plates, and the impact of conical-faced projectiles into plane targets (refs. 5, 6, and 7). The condition for the release of a jet is dependent on the impact velocity, the angle between the colliding surfaces, and the properties of the materials. For an aluminum sphere impacting an aluminum plate at a velocity of 2.5 km/sec, from figure 14 of reference 6, jetting should occur during penetration of the target by the sphere when the angle, θ, between a plane tangent to the sphere and the target surface, at a point on the instantaneous line of contact of projectile and target reaches the critical angle of 28°. Reference 2 gives a theoretical equation for the jet velocity of $V_p \dfrac{1 + \cos(\theta/2)}{\sin(\theta/2)}$, where V_p is the projectile velocity. Experimental results (ref. 6) show that jet velocities at values of θ near the critical angle are lower than that indicated by the theoretical formula. The velocity of the jet V_j must, however, be greater than that of the line of contact or $V_p/\tan\theta$. Therefore we have an upper and lower bound for the velocity of the jet. The value of θ, 28°, when substituted in the two formulas gives $4.7\ \text{km/sec} < V_j < 20.4\ \text{km/sec}$. These velocities are in the range of those given in the above table. It is therefore expected that atomic radiation due to collisions between ejecta atoms and atmospheric atoms could occur. Note, for example, that for the case of an aluminum ejecta atom and a nitrogen molecule, the required velocity, 6.6 km/sec, is only slightly greater than the minimum possible velocity of the jet.

DESCRIPTION OF APPARATUS

The apparatus (fig. 1) consisted of a gun, a test range, and associated instrumentation. A commercial 220 Swift sporting rifle was used to fire sabot-mounted, 1/8-inch-diameter aluminum spheres at a velocity of 2.5 km/sec. The sabot-mounted model was fired into a blast tank containing gas at pressures of about 400 torr, where the sabot and powder gases were stopped. The range consisted of an impact chamber, 11x11 cm in cross section and a 3-meter length of stainless steel pipe connecting the chamber to the blast tank. A 1/2-mil-mylar diaphragm between the blast tank and steel pipe separated the range from the blast tank. The diaphragm was sufficient to maintain the pressure difference of 400 torr and yet not fracture the penetrating model. The 3-meter length of pipe prevented the blast-tank gases from reaching the test chamber until after the luminosity measurements had been made. The test region could be evacuated to 10^{-4} torr with a 4-inch oil diffusion pump. The pressure was measured with a McLeod type gage The inside of the impact chamber was blackened to reduce reflected light. The time variation of luminous intensity of the flash was measured with a DuMont 6292 photomultiplier tube. This tube is sensitive to radiation between the wavelengths 3500 and 5500 Å, or approximately half the visible spectrum. The absolute spectral response of the entire optical train was measured using a ribbon filament lamp, calibrated by the National Bureau of Standards, and a grating monochrometer. The photomultiplier tube, together with a calibrated neutral density filter, was arranged as a "pinhole camera" (fig. 2) with the optical axis in the plane of the target surface. The volume in the test chamber viewed by the system contained all points within approximately 4 centimeters, and uprange, of the optical axis. The phototube output was recorded on two oscilloscopes which provided time axes. One oscilloscope was triggered by the model as it broke a thread of silver painted on the mylar diaphragm. This oscilloscope recorded peak luminosity and an accurate measurement of the time between rupture of the diaphragm and impact, from which projectile velocity was calculated. The second oscilloscope, triggered internally by the flash and sweeping at a much faster rate, measured the variation of luminosity with time. On several rounds the spectra were recorded with a Huet model CI spectrograph which had a camera lens aperture of f/0.7 and a dispersion of 150 Å per mm at 4350 Å and 500 Å per mm at 5500 Å.

RESULTS

In order to determine the effect of radiation from the combustion of aluminum, two rounds were fired at the outset of this investigation - one in air and the other in nitrogen, at pressures of 400 torr. The spectra recorded were found to be different. Those for air contained intense bands of aluminum oxide while those for nitrogen did not. Since this radiation does not occur in chemically inert atmospheres and since it tended to obscure other effects of interest, an attempt was made in the following tests to keep it to a minimum. However, it is of interest that chemical reactions can indeed contribute importantly to the flash of impact.

After this was observed the range was purged with nitrogen before each test and then pumped to the desired pressure. At the lowest pressures, those at about 10^{-3} torr, the pressure and the increase of pressure each minute due to leaks were comparable. Pumping times for these pressures ran several hours, and therefore the composition of the gas was substantially the same as that which leaked into the system, or air. At the higher pressures of this series of tests, those near 2×10^{-1} torr, the composition should differ from that of air due to the higher pressure in comparison with the leak rate and the shorter pumping time required to achieve the desired pressure. Thus the percentage of oxygen is believed to decrease with increasing pressure although the total amount should increase.

Luminosity Studies

It is emphasized that the luminosity measurements refer to radiation between the wavelengths 3500 and 5500 Å from a small volume about the impact point. The luminosity measurements were all made of the flash produced by impacting 1/8-inch-diameter aluminum spheres into aluminum targets at a velocity of 2.5 km/sec. Figure 3 shows two oscilloscope traces of the variation of luminosity of the impact flash with time produced at ambient pressures of 1.6×10^{-3} torr and 8×10^{-2} torr. The impact flash at 1.6×10^{-3} torr is clearly double peaked, while at 8×10^{-2} torr the luminosity of the second peak is nearly masked by the primary flash. At the highest test pressure the secondary radiation appears to be suppressed relative to the peak. Figure 4 is a log-log plot of the initial rate of increase of luminosity in watts per 4π steradians per microsecond, as measured from the initial slope of the luminosity-time curve on the oscilloscope traces versus ambient pressure. The onset of radiation is reported here because the effects of confining the test in a small volume may change the measurement of peak intensity and total radiated energy. This plot which covers a range of pressures from 4×10^{-4} to 2×10^{-1} torr shows that the onset rate of luminosity varies approximately as the cube root of the ambient pressure. The primary radiation for each trace was observed to have a peak intensity which varied directly as the onset rate and occurred at about 2 microseconds after the initiation of flash, a duration (the time from initiation to the decay of one-half peak value) of approximately 5 microseconds, and a similar shape. Hence, the energy of primary radiation, as calculated from the area beneath the luminosity-time curve, is proportional to the onset rate. The energy of primary radiation is of the order of 10^3 ergs at 10^{-2} torr or about one millionth of the projectile kinetic energy.

Spectrographic Studies

Since the proposed lunar application of the impact flash phenomenon test results rests on the analysis of spectra, several tests were recorded with a conventional visible-light spectrograph.

Figure 5 shows six densitometer traces of spectra obtained from impact flash. For each trace the projectile was aluminum and the impact velocity was a nominal 2.5 km/sec. These traces are qualitative in nature and a comparison of relative intensities between different traces should not be attempted. Traces (a) and (b) illustrate the effect of chemical combination. The targets for both traces were aluminum and the ambient pressure was 400 torr. For trace (a) the ambient atmosphere was air and that for trace (b) was nitrogen. The significant difference between the two traces is the appearance of strong aluminum oxide bands in trace (a) and the absence of them in trace (b). Trace (c) is for an aluminum target coated with sodium silicate and an ambient pressure of 8×10^{-4} torr. The predominant feature is the atomic sodium D doublet at about 5890 Å. Two lines are also detectable at about 3950 Å, the approximate wavelength for radiation from excited aluminum atoms. The presence of these latter lines indicates a number of collisions at velocities greater than the threshold of 6.6 km/sec (roughly 2.6 times the impact velocity). For traces (d) and (e) the target was aluminum without sodium silicate and the ambient pressure was 1.2×10^{-3} torr and 2.2×10^{-1} torr. Both traces are very similar and the predominant features are the two lines of aluminum at 3944 and 3962 Å. Manganese line sturcture is seen at 4034 Å along with sodium (not distinguishable in trace (e)). Bands consistent with those expected for aluminum oxide are also present. Manganese is found by chemical analysis to be present in the aluminum alloys of both the target and projectile and, also, in the steel of the impact chamber; sodium, a contaminant, is found on almost everything and aluminum oxide is found on the surfaces of both the target and projectile. Basalt rock was the target for trace (f) and the ambient pressure was 2×10^{-1} torr. The lines of sodium, calcium at 4227 Å, and aluminum and the bands of aluminum oxide are detectable. Sodium, aluminum, and calcium (also an exceptional radiator) are found in basalt as oxides, in addition to which aluminum was, as noted, the material of the projectile.

DISCUSSION

It is obvious from traces (a) and (b) of figure 5 that at pressures of about 400 torr the spectrum of impact flash depends on the composition of the ambient gas. It is also seen, at the low ambient pressures of the present tests, from traces (d) and (e) that, with the exception of the sodium doublet which undoubtedly resulted from salt left on the projectiles and targets during handling, the spectra produced in atmospheres differing in composition and pressure are very similar. This indicates that, at the low ambient pressures over which the luminosity measurements were made, the impact flash mechanism does not vary significantly. Although the spectral quality, at low ambient pressures, is invariant, it is seen from figure 4 that the rise rate of luminosity changes almost one order of magnitude as the ambient pressure changes by almost three. Thus, it is clear that our measurements of luminosity depend on the atmosphere, but it still cannot be said that the mechanism producing flash requires the presence of an atmosphere. If the primary source of luminosity is solely the cratering mechanism, the number and velocities of excited vaporized atoms and molecules, as well as the size, velocity, and temperature distribution of ejecta produced, will be independent of the atmosphere. The atmosphere may, however, hinder these radiating particles leaving the field of view of the measuring photomultiplier tube.

Three physical models may be proposed to explain the observed flash: (1) Excited atoms and molecules are ejected from the crater. These excited particles are raised to energetic states solely by compression and shearing in the process of crater formation. (2) Hot microscopic particles of ejecta, heated during cratering, emerge from the crater and radiate thermally as they move away from the impact point. (3) Microscopic particles of ejecta emerge from the crater and, by virtue of high-speed flight through the surrounding atmosphere, heat, ablate, and radiate in the manner of meteors. The radiation of the first two models depends directly upon the cratering mechanism and would be produced in the absence of an atmosphere. The radiation of the third model depends only indirectly upon the cratering mechanism and directly upon the atmosphere. For this model, ejecta kinetic energy received through cratering is converted to heat and radiant energy through the interaction with the atmosphere.

For the first model to account for the observed pressure dependence of the flash, the energy and therefore the number of atoms and molecules which lose excitation by radiative emission within the field of view must change almost one order of magnitude between the lowest and highest test pressures. Two mechanisms by which this can occur can be postulated: (a) nonradiative decay of the excited atoms and molecules (by collision processes); (b) exit of excited particles from the field of view before they have time to decay. The first mechanism should lead to a reduction in radiative intensity with increasing pressure which is opposite to what has been observed and therefore must be rejected. For the second, excited electronic states, which emit visible radiation upon decay, have a mean life of about 10^{-8} second. In order that the majority of excited particles leave the field of view at a flight distance of 4 cm before decay, they would have to travel at about 4×10^3 km/sec to show the observed pressure dependence. This speed is about one hundred times as fast as the fastest predicted jetting speed. We must, therefore, reject the first model - excitation of atomic states by the primary impact process.

For the second model, it may be argued that microscopic pieces of preheated ejecta radiating thermally, which have a much longer mean life than do individual excited atoms, can account for the observed flash. The increase of energy observed with increasing ambient pressure might then be explained by the increased amount of time spent by the hot radiating ejecta within the field of view because of atmospheric drag. In this event the proportion of continuum radiation relative to line radiation should have increased with increasing ambient pressure. Such an increase is, in fact, shown by comparison of figure 5(b) with 5(c), (d), or (e). However, at pressures from 0.2 to 0.0008 torr, no further large reduction in magnitude of the continuum relative to the lines and bands is observed, and the continuous radiation is, in fact, at a much lower level than line and band radiation from atoms and molecules. Hence, for the pressure range below 0.2 torr, the second model, radiation from high temperature particles of liquid or solid ejecta, does not appear to predominate.

Further evidence that the continuum radiation from hot particles is not the predominant mechanism is obtained from consideration of the observed flash duration and its independence of pressure. Now if the luminosity increases with increasing ambient pressure because the particles are slowed down by atmospheric drag and stay longer in the field of view, then the measured duration should become longer, but this is not observed. The constant duration might be explained if the particle velocities were so high that the stay time in the field of view were short at all ambient pressures compared to the duration of the cratering mechanism producing luminous particles. The particle velocity required to fulfill this condition is about 80 km/sec, an unreasonably high velocity. Furthermore, if the particle velocities were that high, the particles would interact with the surrounding atmosphere in the manner of small meteors and hence would fulfill the requirements of the third model process.

The third model, the interaction of high-speed matter ejected from the crater with the atmosphere, can clearly account for the change in rise rate with pressure. For this model to account for the remaining observations, namely the second peaks on the oscilloscope traces and the time invariance of occurrence of the second and primary peaks, conditions of size and velocity are imposed upon the ejecta. The soundness of these conditions then serve as a check on the validity of this model.

The second peaks on the oscilloscope traces are explained as resulting from the impact of the high-speed ejecta with the walls of the impact chamber. The time between the initiation of the impact flash and the start of the second peak is about 5 or 6 microseconds. The nearest point on the walls from the point of impact is about 5 cm. Thus the average velocity of the ejecta which first strike the chamber walls would be at least about 8 km/sec. The masking of the second peak by the primary peak at high pressure can be explained by the increase of primary radiation and, to a lesser degree, by the decreased velocity and quantity of ejecta reaching the chamber walls as a result of drag and vaporization of ejecta through aerodynamic heating. The invariance of the duration of flash and the time of occurrence of the second peak indicate that aerodynamic deceleration of the particles responsible for flash was not great. This suggests that only a small percentage of the total radiation possible in a large chamber was actually observed. Calculations show that aerodynamic deceleration at the highest test pressures was not significant within the field of view for particles of radii greater than 10^{-5} cm (see the appendix for details of the calculations). The time at which the primary peak starts to decrease signifies that more radiating particles leave than enter the field of view. Figure 3 shows this occurs at approximately 2.5 microseconds after flash is initiated, regardless of pressure, and indicates a maximum particle velocity as high as 16 km/sec. This value, together with that of 8 km/sec, obtained from the secondary peak, lies within the bounds given by jet theory. As mentioned above, particulate matter with velocities equal to or greater than 8 km/sec, at the ambient pressures of these tests, is expected to radiate in the same manner as slow meteors in the free molecule regime. Hence, this model reasonably accounts for all of the observed phenomena of the present tests.

CONCLUDING REMARKS

In the present tests the onset rate of luminosity from high-speed impact was observed to depend upon the ambient pressure of the atmosphere surrounding the target. Luminosity produced solely by the cratering mechanism did not contribute significantly to the observed variation of impact flash. The magnitude of this luminosity contribution, within the field of view, is probably less than or, at most, equal to that observed at the lowest pressures. The interaction of high-speed ejecta with the atmosphere, as concluded by Clark, is consistent with the observed radiation in the present tests.

At higher velocities or with different materials, impact flash resulting solely from the cratering mechanism may constitute a significant quantity of radiation. This difference of materials may explain the results of Gehring. The luminosity measurements of Clark, as well as those of this study, were made of a metal impacting a solid, and Gehring and Sieck's were made on a plastic impacting a granular material. In the shocked impact region, the pressure, which is responsible for the acceleration of ejecta, is expected to be greater for a metal impacting a solid than for a plastic impacting a granular target. The luminosity, produced by ejecta interacting with the atmosphere, may not constitute a significant quantity of radiation in Gehring and Sieck's tests. Also, the fraction of projectile kinetic energy dissipated as heat is known to increase rapidly with target porosity (ref. 8); therefore the principal part of their measured luminosity may be produced entirely by the mechanics of cratering.

At the low ambient pressures of the present tests the observed spectra contain line and band features consistent with the elements known to be present.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Dec. 6, 1963

APPENDIX

CALCULATION OF PARTICLE SIZE FOR WHICH AERODYNAMIC DECELERATION IN THE FREE MOLECULE REGIME IS SIGNIFICANT

The equations of motion and ablation of a meteoric body are (refs. 9 and 10)

$$\frac{dV}{dt} = -\frac{3}{8}\frac{C_D}{r}\frac{\rho}{\rho_m}V^2$$

$$r = r_o e^{-(\eta/12J)(V_o^2 - V^2)}$$

where

C_D	drag coefficient
J	heat of ablation, or amount of heat required to ablate a unit mass
r	radius of body
t	time
V	velocity of body
η	fraction of body kinetic energy lost per unit time which appears as heat in body
ρ	atmospheric density
ρ_m	density of body
$(\ )_o$	value at $t = 0$

Combining the two equations we have

$$\frac{dV}{dt} = -\frac{3}{8}\frac{C_D}{r_o}\frac{\rho}{\rho_m}V^2\, e^{(\eta/12J)(V_o^2 - V^2)}$$

$$\int_o^T dt = \int_{V_o}^{V} \frac{-1}{\frac{3}{8}\frac{C_D}{r_o}\frac{\rho}{\rho_m}e^{(\eta/12J)V_o^2}}\,\frac{e^{(\eta/12J)V^2}}{V^2}\,dV$$

At constant ρ, η and C_D are constant and therefore

$$T = \frac{1}{\frac{3}{8}\frac{C_D}{r_o}\frac{\rho}{\rho_m} e^{(\eta/12J)V_o^2}} \int_{V_o}^{V} - \frac{e^{(\eta/12J)V^2}}{V^2}\, dV$$

Expanding $e^{(\eta/12J)V^2}$ as a power series, we have

$$T = \frac{1}{\frac{3}{8}\frac{C_D}{r_o}\frac{\rho}{\rho_m} e^{(\eta/12J)V_o^2}} \int_{V_o}^{V} - \frac{1}{V^2}\left\{1 + (\eta/12J)V^2 + \ldots + \frac{[(\eta/12J)V^2]^m}{m!} + \ldots\right\} dV$$

Integrating, we have

$$T = \frac{1}{\frac{3}{8}\frac{C_D}{r_o}\frac{\rho}{\rho_m} e^{(\eta/12J)V_o^2}} \sum_{m=o}^{\infty} \frac{(\eta/12J)^m\,(V_o^{2m-1} - V^{2m-1})}{(2m-1)m!}$$

where T is the time, in terms of a convergent series, for the velocity to decelerate from V_o to V.

For an aluminum body, of radius r_o, moving in the free molecule regime with velocity V_o, in an ambient air atmosphere of pressure 2×10^{-1} torr,

$$C_D = 2$$

$$\rho_m = 2.7\ \frac{gm}{cm^3}$$

$$\eta = \text{at most, } 1$$

$$\rho = 3.4\times10^{-7}\ \frac{gm}{cm^3}$$

Taking as the heat of ablation of aluminum, its heat of vaporization,[1] one has

$$J = 8.34\times10^{10}\ \frac{\text{ergs}}{\text{gm}}$$

Defining a significant velocity decrease as one-tenth its initial value $V = (9/10)V_o$, we can solve for T, the time for this to occur, in terms of r_o,

for $V_o = 10$ km/sec

$$T = \frac{r_o\ \text{cm}}{1.6\ \frac{\text{cm}}{\text{sec}}}$$

for $V_o = 20$ km/sec

$$T = \frac{r_o\ \text{cm}}{2.4\ \frac{\text{cm}}{\text{sec}}}$$

The maximum time available, for such a velocity decrease to be observed, is of the order of the duration of flash, or 5 microseconds. Hence, bodies of initial radius r_o for which

$$r_o > 8\times10^{-6}\text{cm}\ , \qquad \text{for}\ \ V_o = 10\ \text{km/sec}$$

and

$$r_o > 1.2\times10^{-5}\text{cm}\ , \qquad \text{for}\ \ V_o = 20\ \text{km/sec}$$

will not decelerate significantly during the time of observation.

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[1] J should also include $\int_{T_i}^{T_V} C_p dT$; hence, the value of J reported is a minimum value.

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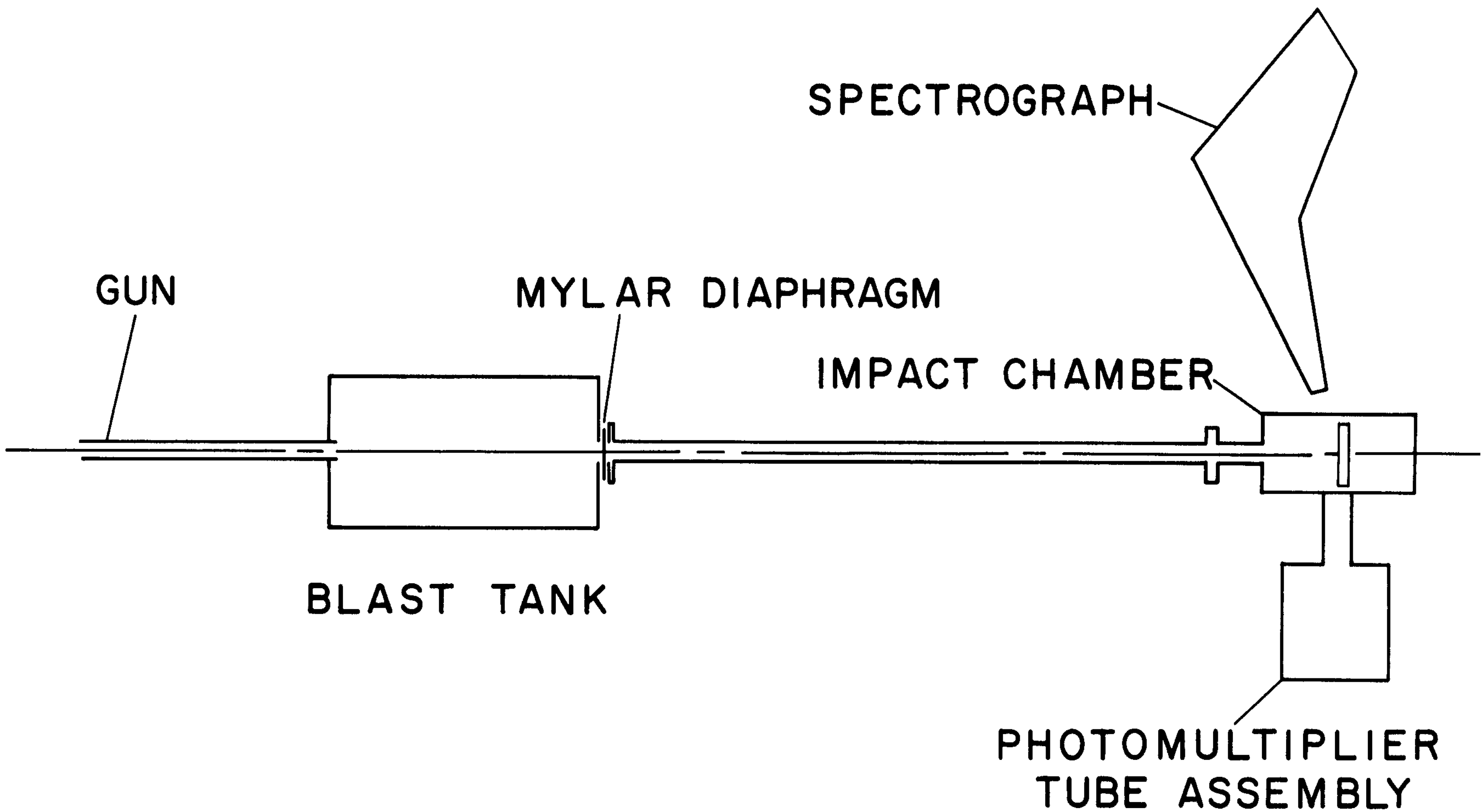

Figure 1.- Schematic drawing of experimental apparatus.

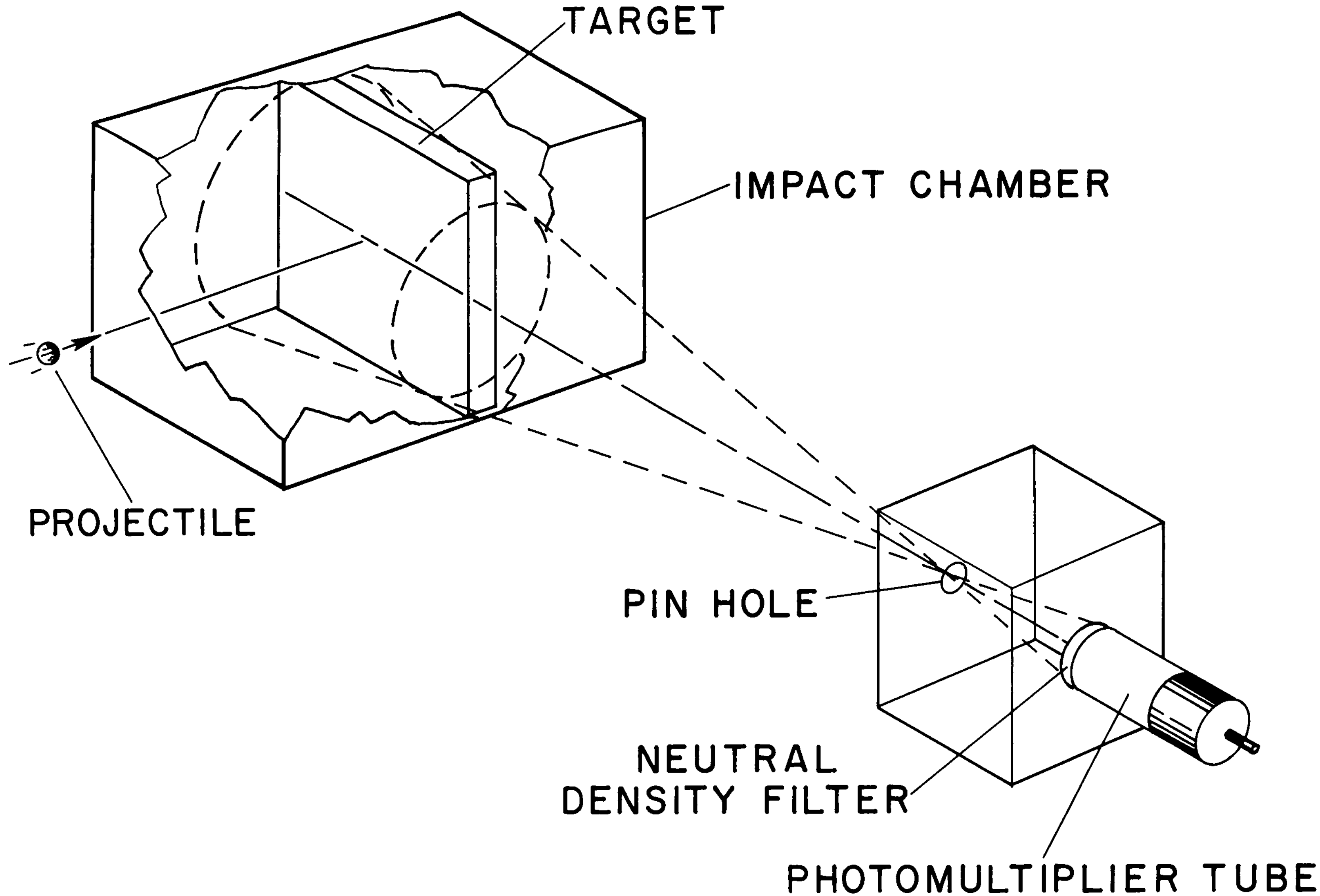

Figure 2.- Photomultiplier-tube assembly.

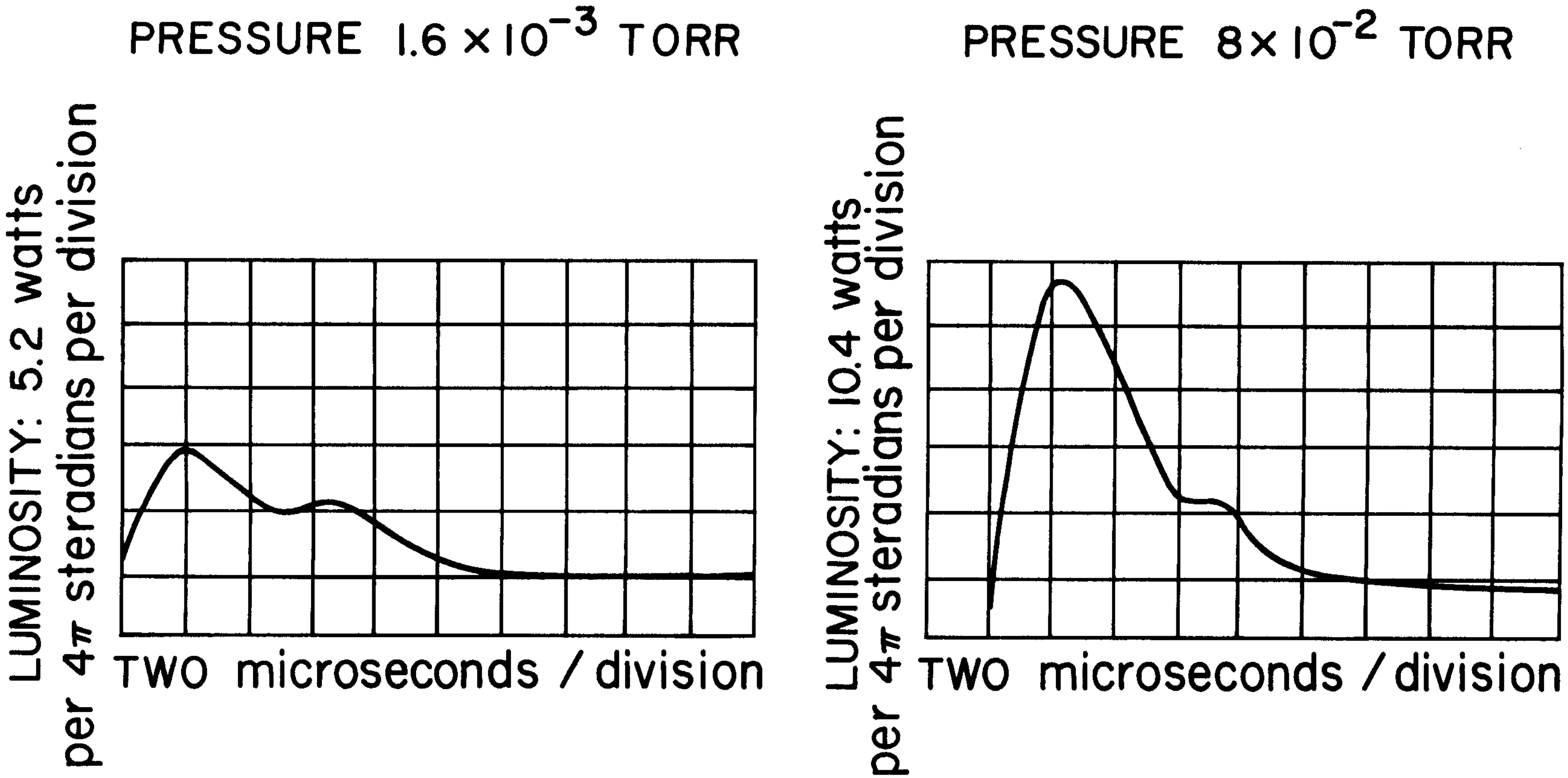

Figure 3.- Photomultiplier-tube-oscilloscope traces.

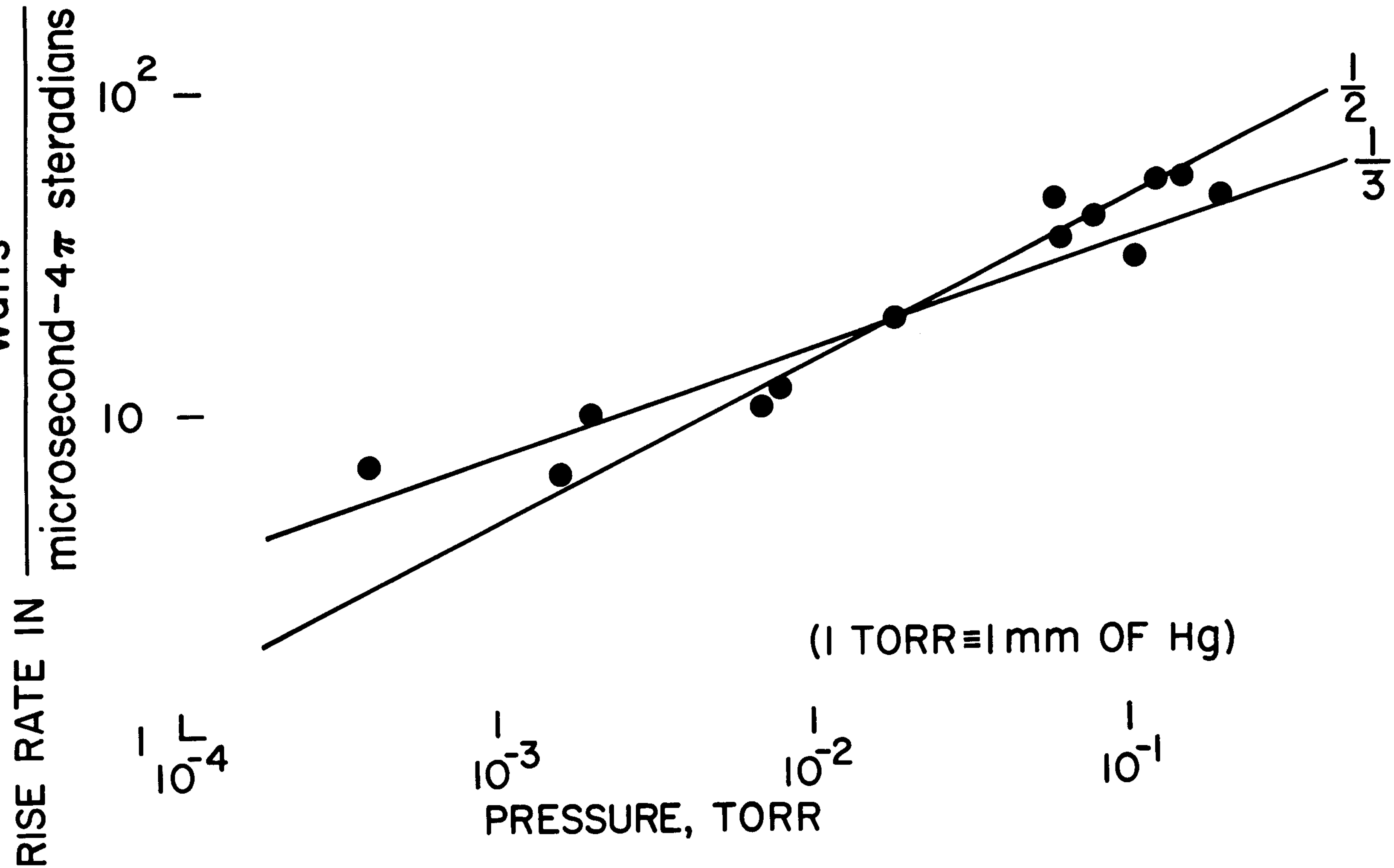

Figure 4.- Rise rate of luminosity versus pressure.

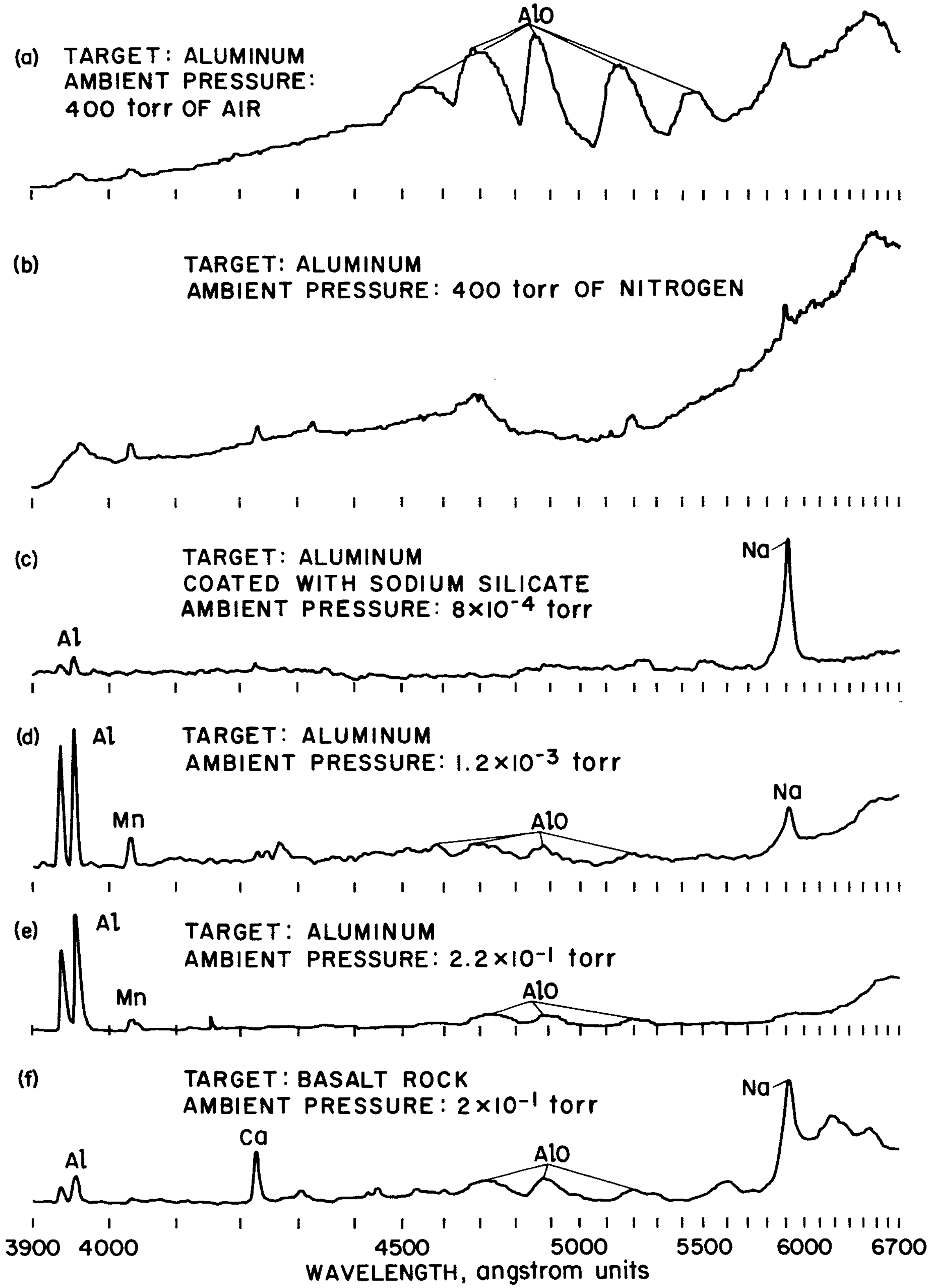

Figure 5.- Densitometer traces.